Available online at www.sciencedirect.com
ScienceDirect
Physics Procedia 69 (2015) 185 – 188
Physics Procedia

10 World Conference on Neutron Radiography 5-10 October 2014

Inexpensive Neutron Imaging Cameras using CCDs for Astronomy

A.W. Hewat[a] *

[a]NeutronOptics Grenoble, 8 Allée des Pampres, 38640 Claix, FRANCE

Abstract

We have developed inexpensive neutron imaging cameras using CCDs originally designed for amateur astronomical observation. The low-light, high resolution requirements of such CCDs are similar to those for neutron imaging, except that noise as well as cost is reduced by using slower read-out electronics. For example, we use the same 2048x2048 pixel "Kodak" KAI-4022 CCD as used in the high performance PCO-2000 CCD camera, but our electronics requires ~5 sec for full-frame read-out, ten times slower than the PCO-2000. Since neutron exposures also require several seconds, this is not seen as a serious disadvantage for many applications. If higher frame rates are needed, the CCD unit on our camera can be easily swapped for a faster readout detector with similar chip size and resolution, such as the PCO-2000 or the sCMOS PCO.edge 4.2.

Selection and peer-review under responsibility of Paul Scherrer Institut

Keywords: Inexpensive Neutron Imaging Cameras; Interline CCDs; Astronomical CCDs; Kodak KAI-4022 CCD

1. Introduction

Although ILL had been an early pioneer of neutron imaging, with an extremely high flux beam line and a very fast camera capable of imaging the flow of oil and gas in real time in an operating engine, this project was discontinued. The ILL diffraction group later developed two related projects. One was a simple neutron camera to locate samples in the neutron beam (Hewat 2007). The other was a much more sophisticated multi-CCD neutron camera to image reciprocal space rather than real space (Hewat 2006, Ouladdiaf et al 2011), constructed by Photonic Science UK (1985). The simplest form of this "Laue" camera consisted of two CCDs imaging the diffraction pattern backscattered from a single crystal. By increasing the number of CCDs to 16 an almost complete

* Corresponding author. Tel.: +33-476-984168; fax: +33-958769841.
E-mail address: alan.hewat@neutronoptics.com

Selection and peer-review under responsibility of Paul Scherrer Institut
doi:10.1016/j.phpro.2015.07.026

4π scattering angle could be covered, not just backscattering, and the Bragg intensities could be measured to yield the atomic structure after transforming to real space. This experience was used to develop neutron cameras for imaging, via a small spin-off company, NeutronOptics Grenoble.

2. Simple neutron imaging cameras for sample alignment

The original Polaroid neutron camera was a brilliant innovation. It used commercially available components from the consumer market, so it was very cheap and easy to use. It only required the addition of a scintillator in contact with the film to produce a very efficient, high resolution camera with no mechanical or electrical adjustments. Our ambition was to produce an equally simple camera using modern consumer components (CCDs).

Fortunately there are some consumer markets that require low-light CCDs, for example the amateur astronomy market. In fact the CCD chips in these cameras are often the same chips found in much more expensive scientific cameras - those made by Sony and the former Kodak. The Sony ExView HAD chips are especially efficient and generally have very low noise. For our simple neutron alignment cameras, we chose CCD units using the 1/2" Sony ICX419ALL and later the more efficient new ICX829ALA. We also use the larger 2/3" Sony ICX285AL, which is popular in many sensitive industrial cameras. These monochrome chips contain large pixels with micro lenses over each pixel, so are very efficient in collecting light, while containing enough pixels for 100μm resolution imaging over areas of up to 100x100mm. For the other components, we use the same scintillators and front surfaced mirrors that are found in the most expensive neutron cameras. We have manufactured over 200 such simple cameras.

3. Inexpensive High Resolution Imaging cameras

Large neutron laboratories usually develop and construct their own high resolution neutron cameras, but smaller laboratories don't have the necessary experience or facilities for that. In 2010, an international atomic energy agency asked NeutronOptics Grenoble to construct a simple 200x200 mm high resolution neutron imaging camera suitable for a developing laboratory.

The design of this camera was simplified so that there were no moving parts. Instead of moving the CCD unit and/or lens in the box to change the field-of-view (FOV), the CCD unit was fixed to the exterior of the box with the lens inside. The FOV, and indeed the scintillator, could be changed by fitting front-end sections of different lengths to the L-shaped camera box (figure 1). The lens, being mounted on a standard Nikon F-mount bayonet, can be easily exchanged. Construction details are given in the user manual (NeutronOptics 2007).

Fig. 1. (a) 200x200mm high resolution neutron or x-ray camera; (b) 100x100mm compact high resolution neutron or x-ray camera

Otherwise our advanced camera used the best parts available - a PCO-2000 CCD unit with a 50mm Nikkor f/1.2 lens, front- surfaced mirrors and RC-TriTec scintillators developed with PSI. To achieve even greater cost savings for developing laboratories, we found that the same Kodak chip used in the PCO-2000 is also used in inexpensive astronomy cameras; the difference is that the readout is much slower to reduce costs and readout noise (table 1). That is not a problem for neutron imaging on low flux sources, when exposure times are also long.

Table 1. Comparison of 2048x2048 pixel detectors with the NeutronOptics LF40+ for neutron imaging.

	NeutronOptics LF40+	**PCO.2000**	**PCO.edge gold 4.2**
Type	Interline transfer CCD KAI-04022	Interline transfer CCD KAI-04022	Scientific sCMOS
Resolution pixels	2048 x 2048	2048 x 2048	2048 x 2048
Sensor active area mm	15.2 x 15.2	15.2 x 15.2	13.3 x 13.3
Pixel size µm	7.4 x7.4	7.4 x7.4	6.5 x 6.5
Quantum efficiency	55%	55%	> 70%
Full well capacity e-	40,000	40,000	30,000
Readout noise e-	11	6	1
Readout range A/D*	16-bits	14-bits	16-bits
Dark current e-/pixel/s	0.01 @ -20 °C	0.01 @ -20 °C	< 0.02 @ -30 °C
Frame rate fps max**	0.2	2.2 to 14.7	40 or 100
Exposure time s	500 ms .. unlimited	500 ns .. unlimited	500 µs .. 60 s
Binning h,v	x1 x2 x4 x8	x1 x2 x4 x8	x1 x2 x4
Mount	Nikon F-mount	Nikon F-mount	Nikon F-mount
Cooling	Peltier Δ-40 °C	Peltier Δ-50 °C	Peltier Δ-30 °C
Trigger input signals	Software trigger	Hardware trigger	Hardware trigger
Data interface**	USB 2.0	USB 3.0	USB 3.0
Relative cost	1	5	4

* The dynamic range is the ratio Full well capacity on Readout noise, and is lower than the nominal A/D readout.
** USB 2.0 is limited in practice to ~280Mbits/s i.e for a 2048x2048x16 bit camera to ~4 fps. USB 3.0 is limited to ~4000Mbits/s or ~64 fps for 16-bit readout.

Table 1 shows that the PCO.2000 uses the same CCD as our LF40+ with similar imaging performance, except that it uses more expensive electronics with much faster readout and higher frame rates. The main advantage of the PCO.edge gold 4.2 sCMOS over CCD detectors is the much faster frame rate for lower readout noise (but higher dark current, which limits exposures). sCMOS detectors are most suited for fast data acquisition, while CCD detectors are most suited for low flux neutron imaging with longer acquisitions.

NeutronOptics high resolution cameras are fitted with a 42mm T2-mount on the camera side, to screw into the T2-mount on our CCD units. The Nikkor 50mm f/1.2 lens distance can then be adjusted and fixed using a simple screw-clamp. PCO and Photonic Science sCMOS cameras can also be supplied with T2-mount or Nikon F-mount adapters, so if higher frame rates are required, such alternatives can be screwed directly onto our camera body.

4. Results obtained on low-flux neutron and x-ray sources

Several of our high resolution neutron and x-ray cameras have been installed recently throughout the world. As examples we show results obtained with thick objects: fig. 2a) valves and batteries on a low flux 300kV pulsed x-ray source at the Colorado School of Mines and fig. 2b) optically invisible repairs to a break in an historic vase on the low flux 1.3MW TRIGA reactor in Thailand. These cameras both use our LF40+ detector and 50mm Nikkor f/1.2 lens. The 200x200mm neutron camera (fig. 1a) uses a 0.2mm PSI/RC-Tritec scintillator, while the 100x100mm x-ray camera (fig. 1b) uses a fine un-mounted CAWO OG16 x-ray scintillator behind a 0.5mm carbon fiber window. In fact, x-ray and neutron scintillators and windows can be easily swapped in-situ on both cameras.

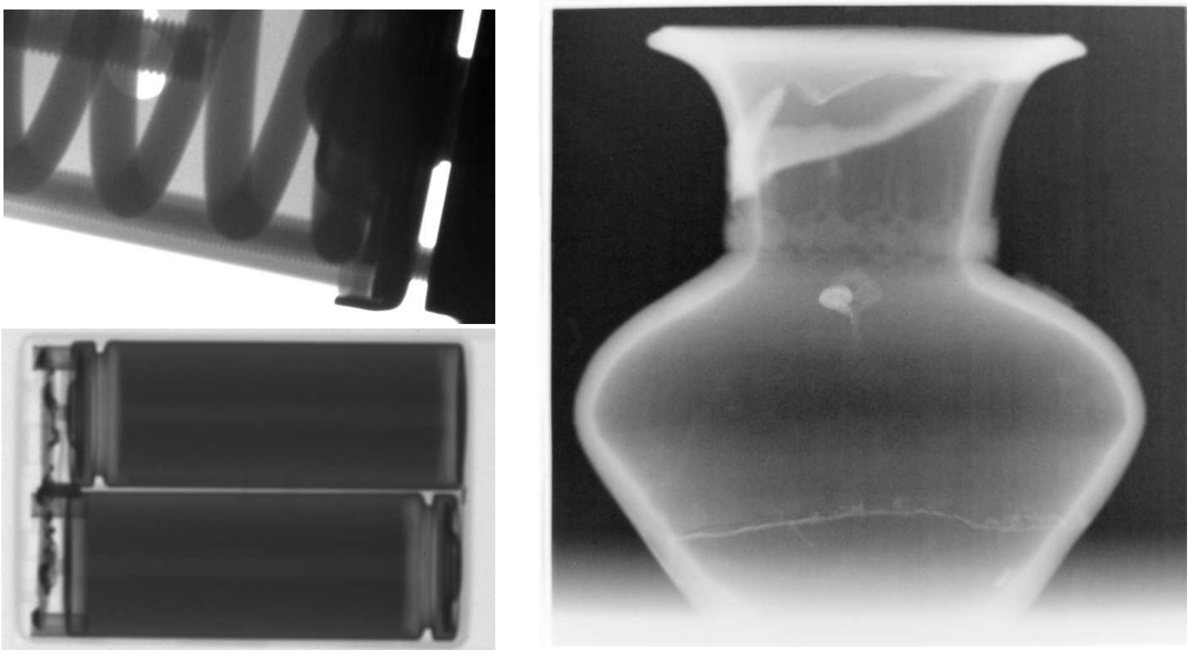

Fig. 2. (a) 300 kV pulsed x-ray images (Colorado Mines 2014); (b) 200x200mm neutron image on 1.3 MW TRIGA reactor (TINT 2014)

5. Conclusions

By using mass produced CCD units designed for the amateur astronomy community, we can greatly reduce the cost of a high resolution neutron or x-ray camera, while retaining the ability to capture high quality, low noise images. The main compromise is that read out times become several seconds, but for many purposes, especially on low flux sources, that is not a real problem. If faster frame rates are required, our CCD unit can be easily swapped for more expensive CCD or sCMOS detectors.

Our simple neutron alignment cameras have been supplied to most of the world's neutron scattering laboratories, and our high resolution neutron imaging cameras have already been supplied to laboratories in Egypt, Algeria, Thailand, Russia and the USA.

Acknowledgements

We would like to thank Drs E. Lehmann and Ch. Grünzweig (PSI), B. Walfort (RC-Tritec), B. Schillinger (FRM2) and N. Kardjilov (HZB) for advice and assistance, and of course our friends and colleagues at ILL and Photonic Science, in particular Patricia Tomkins, Carl West and Daniel Brau for a long collaboration.

References

Colorado Mines 2014 courtesy Prof. Jeffrey C. King,, Interim Director, Nuclear Science and Engineering Program, Colorado School of Mines
Hewat, A.W. 2006. High Flux Diffractometers on Reactor Sources Physica. B 385-86, 979-984 http://hewat.net/science/papers/2006-ICNS.pdf
Hewat, A.W. 2007. ILL News June p.9 A New CCD Alignment Camera https://www.ill.eu/nc/html/quick-links/publications/ill-news/
NeutronOptics 2007 http://neutronoptics.com/cameras.html#advanced & http://hewat.net/nog/Manual-NeutronOptics-Imaging-Camera.pdf
Ouladdiaf, B., Archer, J., Allibon, J., Decarpentrie, Ph., Lemée-Cailleau, M-H., Rodriguez-Carvajal, J., Hewat, A.W., York, S., Brau, D. and McIntyre, G.J. 2011. CYCLOPS – a reciprocal-space explorer based on CCD neutron detectors. J. Appl. Cryst. 44, 392–397
Photonic Science UK 1985 http://www.photonic-science.com/
TINT 2014 courtesy of Dr.K Sasiphan, Thai Institute of Nuclear Science and Technology and Mr Tanut Jomkaew, Nuclear Systems Thailand